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George Haller

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In this project, we have sought to develop exact criteria for steady and unsteady aerodynamic separation in two- and three-dimensional fluid flows. We also aimed to verity our results numerically and experimentally, and develop new algorithms for controlling the location and shape of unsteady separation.

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Final Report on

Control of Unsteady Separation: A Dynamical Systems Approach

AFOSR GRANT NO. F49620-03-1-0200

2003-2005

George Haller
Department of Mechanical Engineering
MIT, Cambridge, MA 02139

Objectives

In this project, we have sought to develop exact criteria for steady and unsteady aerodynamic separation in two- and three-dimensional fluid flows. We also aimed to verify our results numerically and experimentally, and develop new algorithms for controlling the location and shape of unsteady separation.

Approach

In our approach, separation structures are identified as unstable manifolds emanating from a no-slip fluid boundary. Such structures remain hidden in instantaneous pressure, vorticity or streamline plots of unsteady fluid flows, but become the dominant flow structures observed in dye or smoke visualization of separation. As an illustration, the upper part of Fig. 1 shows our experiment visualizing separation in the form of a thin dye streak emanating from the boundary. The lower part of the same figure shows the linear approximation of the separation profile obtained by applying our criteria to a direct numerical simulation of the same flow.

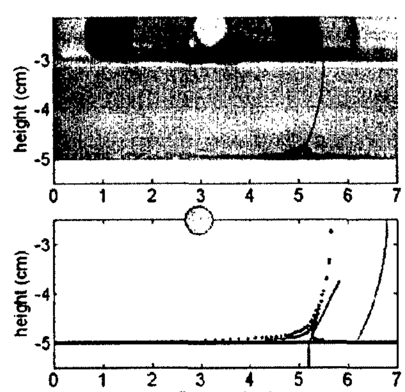

Figure 1: Separation spike (unstable manifold) visualized by dye (upper figure), and found in a related direct numerical simulation by our exact separation criterion. The criterion gives a linear approximation for the separation profile (straight line), which notably differs from the separation line inferred from instantaneous streamlines (curve on the right). See [7] for details; joint work with Tom Peacock (MIT).

Results

1. Three-dimensional separation theory

We have developed an exact theory of three-dimensional steady separation [6]. Our theory predicts separation lines and separation angles from on-wall measurements of wall shear and wall pressure. The theory also states that there are only four topologically distinct robust separation geometries with uniquely defined separation lines. We show these possible geometries in Fig. 2.

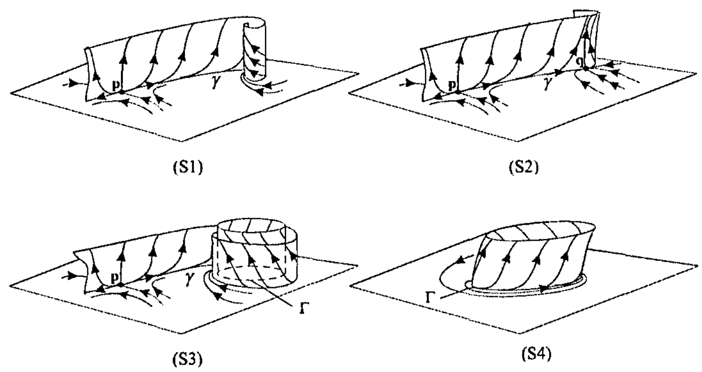

Figure 2: The four basic separation patterns that may arise on the surface of a three-dimensional body.

We have verified the predictions of our new 3D theory in direct numerical simulations of a backward-facing step and a lid-driven cavity flow [1]. Figure 3 shows separation manifolds obtained for the step flow.

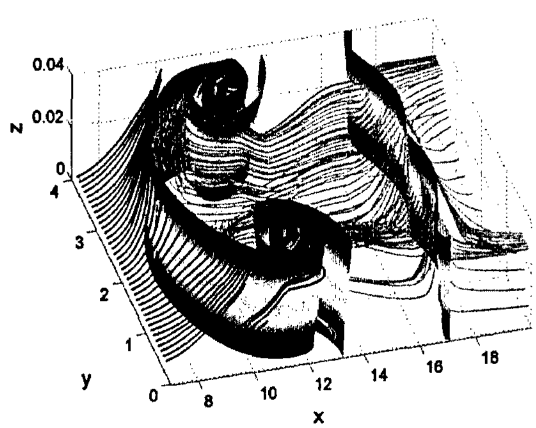

Figure 3: Leading-order separation surfaces constructed from on-wall pressure- and skin-friction measurements on the top wall behind a backward-facing step. Also shown are nearby streamlines whose geometry validates the separation surfaces.

2. Two-dimensional separation control

Our kinematic theory of two-dimensional separation (develop under prior AFOSR support) enables the design of controllers that reduce separation or reattachment zones to a required size [5]. We demonstrated this in direct numerical simulations of channel- and step flows. As an example, Fig. 4 shows the reduction of the reattachment zone behind a backward-facing step using our control-of-invariant-manifolds approach.

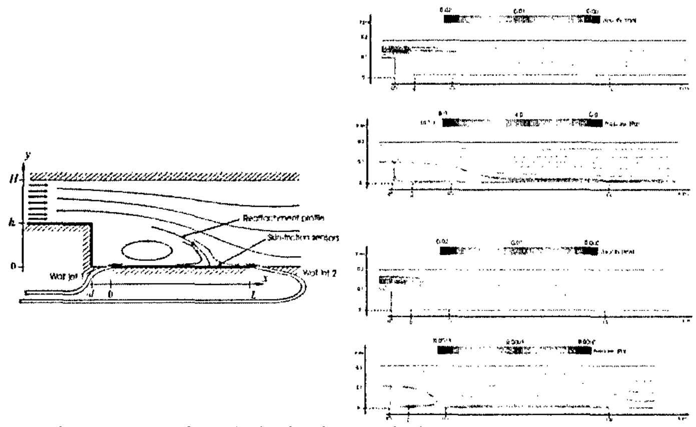

Figure 4: Closed-loop reattachment control behind a backward-facing step. The upper right figure shows velocities and streamlines in the open-loop system; the lower right figure shows the same for the closed-loop system. The controller was designed to reduce the reattachment length from approximately 0.3m to 0.2m.

3. Reduced flow modeling for flow control

For Navier-Stokes flows, we have derived a hierarchy of localized PDE models (*Reduced Navier-Stokes* or *RNS* equations) to approximate the evolution of the skin friction and the wall pressure [3]. We proved that all members of the RNS model hierarchy are well posed. We also found that in short-time numerical simulations, the RNS equations show close agreement with skin-friction τ and wall-pressure-gradient γ computed from direct Navier-Stokes simulations.

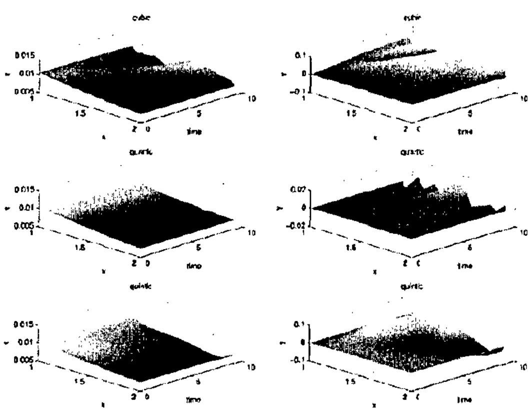

Figure 5: Evolution of the τ and γ profiles in the cubic, quartic, and quintic RNS equations for the Blasius boundary layer flow. At the nondimensional time t=0, the profiles agree with the exact solution.

4. Applications of coherent structure detection outside fluid mechanics

We have also explored the detection of *Lagrangian Coherent Structures* or *LCS* (developed for fluid flows under prior AFOSR award) for problems outside the realm of fluid mechanics. We used our LCS techniques to uncover the phase space geometry of nonlinear vibration absorbers [4], and find a condition for cell-death in a model of biological signaling networks [2] (see Fig. 6).

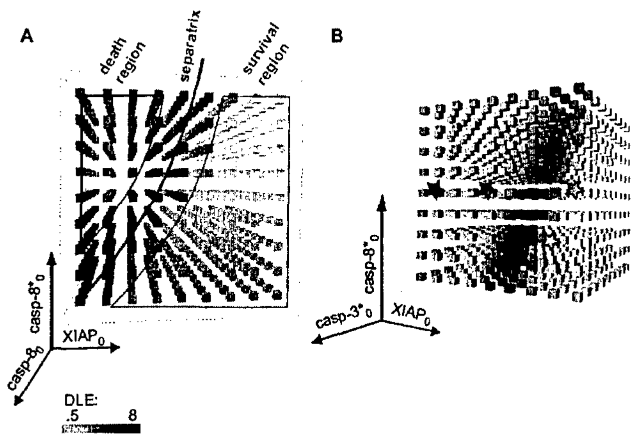

Figure 6: An LCS (stable manifold) separating the phases space of a cell model into death and survival regions.

Personnel Supported

George Haller (PI), Weijiu Liu (postdoc), Guus Jacobs (postdoc), Olivier Grunberg (graduate student), Amit Surana (graduate student), Yildiray Yildiz (graduate student), Mohammad-Reza Alam (graduate student), Raul Cotal (graduate student).

Publications resulting from this award

1. A. Surana, G. B. Jacobs, & G. Haller, **Extraction of separation and reattachment surfaces from 3D steady shear flows**, submitted to *AIAA J.* (2005)

2. B. Aldridge, G. Haller, P. Sorger, & D. Lauffenburger, **Direct Lyapunov exponent analysis enables parametric study of transient signaling governing cell behavior**, submitted to *IEE Proc. Systems Biology* (2005)

3. M. S. Kilic, G. B. Jacobs, J. S. Hesthaven & G. Haller, **Reduced Navier-Stokes equations near a flow boundary.** submitted to *Physica D* (2005)

4. K. El Rifai, A. K. Bajaj, & G. Haller, **Global dynamics of an autoparametric spring-mass-pendulum system**, submitted to *Nonlinear Dynamics* (2005).

5. M. R. Alam, W. Liu, & G. Haller, **Closed-loop separation control: An Analytic approach,** *Phys. Fluids.* in press (2006)

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7. T. Peacock, R. Coral & G. Haller, **Exerimetal validation of the Kinematic Theory of Unstady Separation,** *AIAA technical paper* 2005-4903 (2005).

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11. W. Liu & G. Haller, **Inertial manifold and completeness of eigenmodes for unsteady magnetic dynamos,** *Physica D* **194** (2004) 297-319.

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